The Use of Harmonic Drives on NASA's Mars Exploration Rover

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Abstract

The Mars Exploration Rover (MER) mission will send two 185 kg rovers to Mars in 2003 to continue the scientific community's search for evidence of past water on Mars. Of the 33 motor-driven actuators that these twin robotic vehicles will carry, 19 incorporate harmonic drives. Two subsystems on the rover that use harmonic drives are the High Gain Antenna Gimbal and Wheel Drive and Steering Actuators. While harmonic drives have been used on the Red Planet before, documented experimental data on the their performance at temperatures as cold as –70C is not abundant. Therefore, engineering units of actuators within these subsystems were built and tested so that their performance may be characterized at various temperatures, speeds, and loads.

Mars Exploration Rover (MER) Mission Overview

Between June and July 2003, two new powerful rovers will begin their 7 month journeys to Mars, launched separately aboard two Boeing Delta 2 launch vehicles [1]. The twin 185 kg rovers are significantly larger and more capable than the Sojourner rover that captured the world's attention in 1997. The two Mars Exploration Rovers will carry a suite of instruments that will enable the scientific community to continue its search for evidence of liquid water that may once have flowed on Mars.

The Cruise-Entry-Descent-and Landing (CEDL) system resembles the system used on Mars Pathfinder [1]. The spacecraft will jettison its cruise stage about 15 minutes before it enters into the atmosphere. It will then enter into the atmosphere at an altitude of 125 km and velocity of 5.7 km/s. At an altitude of about 12 km, the spacecraft will deploy its supersonic parachute to slow its velocity from approximately 430 m/s to approximately 90 m/s. During this descent, the spacecraft will jettison its heatshield and lower the lander from the backshell using a bridle. An exploded view of the Entry System is shown in Figure 1. Approximately 10 seconds prior to landing and at an altitude of 355m, airbags will inflate and surround the tetrahedral-shaped lander. Approximately 7 seconds prior to landing and at an altitude of 150m, the lander will fire its Rocket-Assisted Decelerator (RAD) rockets and Transverse Impulse Rocket System (TIRS) rockets to further decrease its velocity. Upon impact with the Martian ground, the lander's maximum vertical and horizontal velocities will be approximately12 m/s and 20 m/s, respectively. The airbags will cushion the lander's impact, limiting the deceleration to approximately 30 g's. The lander will then bounce approximately ten times prior to resting on the surface. Finally, the airbags will deflate and retract, thus permitting the lander to open its petals and reveal the rover inside, as shown in Figure 2.

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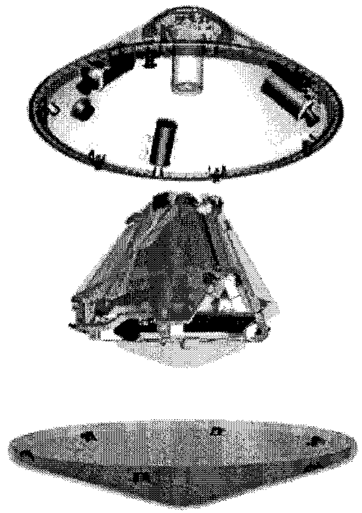

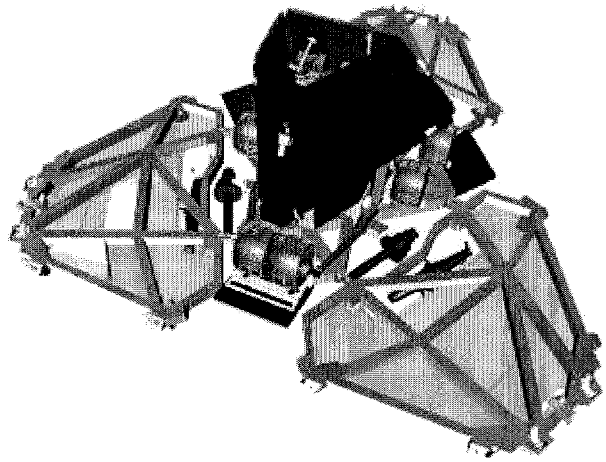

Figure 1: Exploded View of Entry System **Figure 2: Stowed Rover Inside Deployed Lander**

Unlike on the Mars Pathfinder mission, all of the scientific instruments on this mission are attached to the rovers and are therefore mobile. Once the rovers deploy from their launch-locked configuration, they will begin their studies of Mars by taking full panoramic color pictures of their respective landing sites. The rovers will then egress off their respective landers and begin their much-anticipated journeys. The deployed rover is shown in Figure 3.

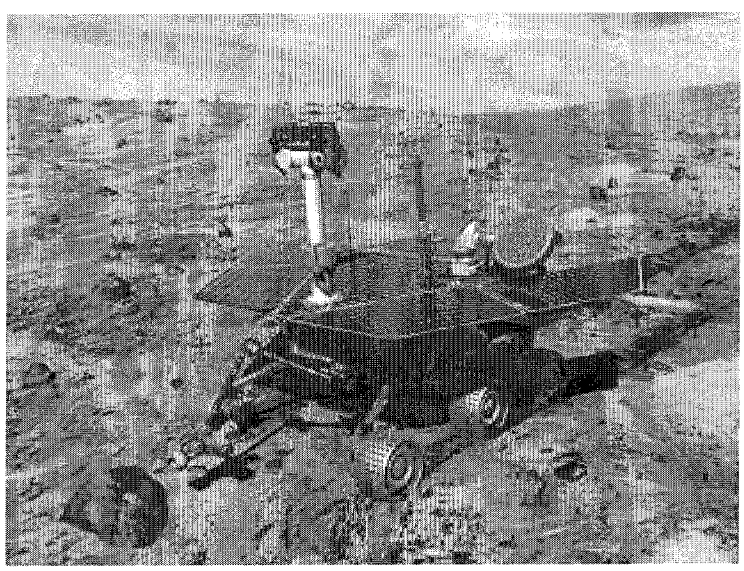

Figure 3: Deployed Mars Exploration Rover

Using images and telemetry received daily from the rovers, scientists and engineers will command the rovers to evaluate the composition and microscopic texture of specific rock and soil targets of interest. During its 90-day lifetime, the rover will traverse up to 100 meters per day and use the following suite of scientific instruments [2]:

- *Panoramic Cameras* generate high-resolution color images of the rover's surroundings to help scientists decide which rocks and soil to analyze in further detail
- *Mini-Thermal Emission Spectrometer* obtains high quality mid-infrared (5-25 micron) spectra to estimate the mineral composition of rocks and soil up to 100 meters from the rover
- *Mössbauer Spectrometer* identifies the composition and abundance of iron-bearing minerals that are difficult to detect
- *Rock Abrasion Tool* removes dust and weathered rind from rocks to reveal native rock structure underneath
- *Microscopic Imager* generates close-up images of rocks and soils which will be used in conjunction with the observations from other instruments
- *Alpha-Particle X-ray Spectrometer* determines the elemental composition of selected rocks and soils
- *Magnet Array* collects magnetic portions of airborne dust for analysis by other instruments

The mobile rover uses its thirty-three motor-driven actuators to satisfy both its engineering and scientific requirements. Of these actuators, the following 19 actuators use harmonic drives:

- High Gain Antenna Gimbal (2)
- Wheel and Steering Assemblies (10)
- Pancam Mast Assembly (4)
- Instrument Arm (3)

The REO20 and RE25 Maxon brushed DC motors were modified for use in all MER mechanisms. For additional commonality across the system's actuations, planetary gearboxes were directly integrated with the two motors and provided the initial gear reduction. A 4.333:1 gear ratio per planetary stage was chosen.

High Gain Antenna Gimbal (HGAG)

During landed operations, the MER rovers communicate with Earth using three different systems: a Low Gain Antenna (LGA), a UHF antenna, and a High Gain Antenna (HGA). The omni directional LGA is suitable for low data rate communication when the rover's orientation is unknown. The omni directional UHF antenna is suitable for high data rate communication but is only usable when the orbiting Mars Odyssey or Mars Global Surveyor spacecraft is overhead. Approximately half of all planned communications use the HGA, a 0.28m diameter antenna that transmits data at 1850 bits per second. Since the HGA is not omni directional, the rover must point the HGA towards Earth using a two-axis gimbal called the High Gain Antenna Gimbal (HGAG). Figure 4 shows an isometric view of the High Gain Antenna Assembly, and Figure 5 shows a cross section view of the HGAG's azimuth drive.

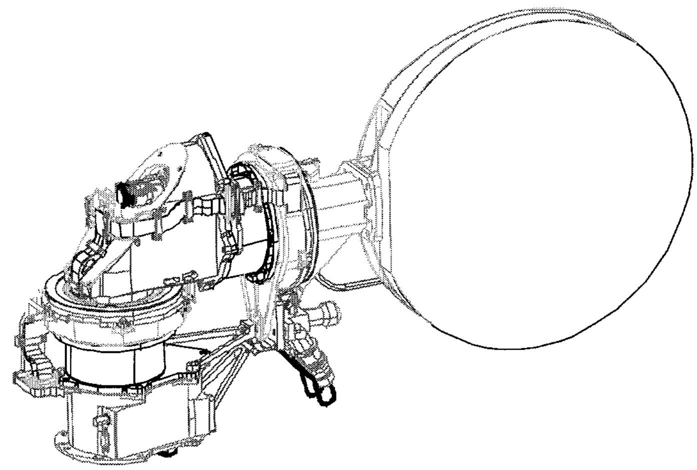

Figure 4: High Gain Antenna Assembly

The HGAG can use its azimuth and elevation drives to obtain a hemispherical field-of-regard. The drive trains are identical, have a total reduction of 5425:1, and consist of:

- A Maxon REO20 brush motor
- A 3 stage 81.37:1 planetary gearbox
- A 1.333:1 spur gear stage
- A size 14 SHF 50:1 harmonic drive

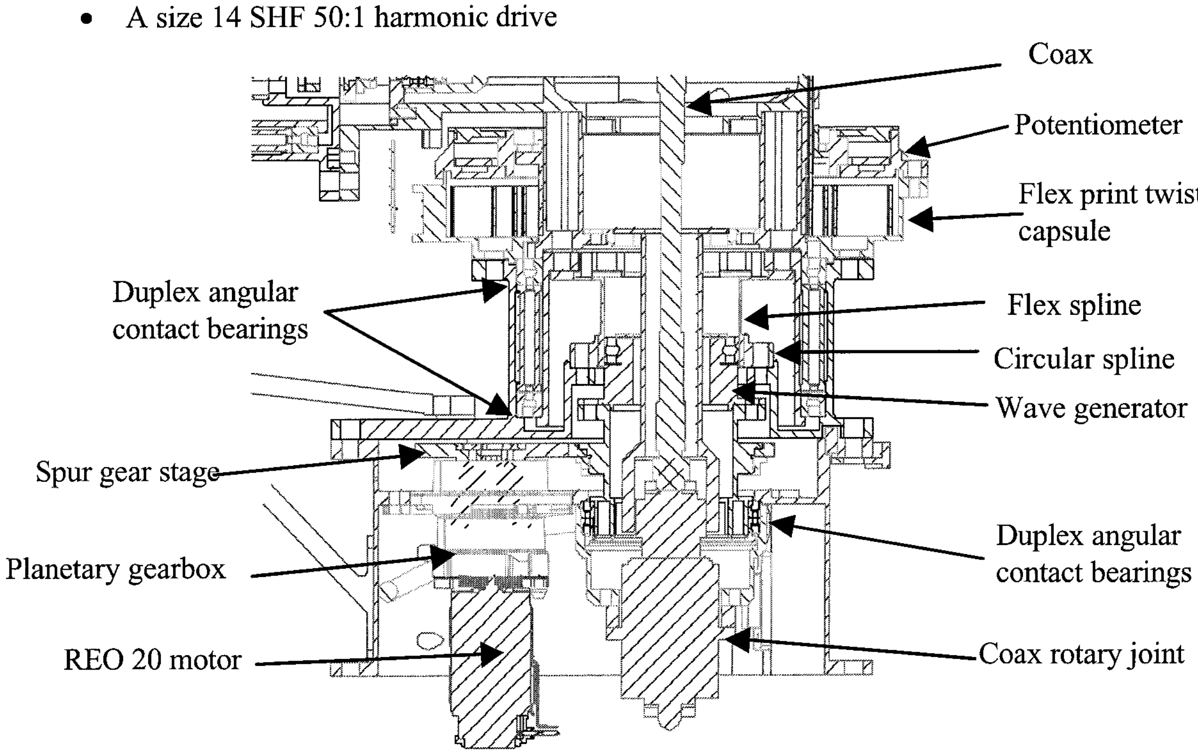

Figure 5: HGAG Section View

The principle requirements that drive the HGAG's design include:

- Accommodating and minimizing the length of RF coaxial cable
- Slewing at 3 degrees/second
- Stowing within a heavily constrained volume
- Meeting all torque, speed, and accuracy requirements between –70C and +45C
- Limiting the uncertainty in mechanical knowledge and control = +/- 0.5 degrees
- Limiting the number of revolutions on the motor during Earth testing and Mars operations to 2.5 million

The HGAG employs a harmonic drive output stage because:

- The harmonic drive reduces the effect of backlash in earlier gear stages
- The harmonic drive occupies a small volume
- The SHF harmonic drive accommodates RF coaxial cables that are concentric to the drive axes. Since the maximum effective diameter of the coaxial cable fittings is 18.8 mm, the maximum wave generator bore diameter of 19 mm was used. An Oldham coupling was not used, because it would reduce the effective bore diameter of the harmonic drive.
- The harmonic drive is torsionally stiff enough to meet the HGAG's pointing requirements yet compliant enough to limit the loads induced in the gear train when the drives are commanded into their hardstops

The drives must possess sufficient torque to overcome parasitic losses internal and external to the gear train while articulating on a 40-degree slope. On earth, this output torque corresponds to approximately 5.7 N-m for the azimuth drive and 1.3 N-m for the elevation drive. On Mars, this output torque corresponds to 2.8 N-m for the azimuth drive and 1.2 N-m for the elevation drive. Included in these torque values are non-gravity dependent drags from the flex print within twist capsule, the rotary joint, and seals. The output torque requirement for the azimuth drive exceeds the output torque requirement for the elevation drive, because the latter is nearly balanced. The magnitude of both these output torques is fairly small and is therefore not a significant design driver. However, overcoming the parasitic torque losses internal to the drive train is a significant design driver, because the viscosity of the Bray 815Z base oil in the Braycote 601 EF grease in all the bearings can reach 12,000 cST at –70C [3]. To minimize these parasitic losses, all bearings within the HGAG will be grease-plated and not filled with grease to a larger percentage.

When driving into its hardstop at the 34V maximum operating voltage, the peak torque in the harmonic drive may reach as high as 52 N-m. To ensure that the harmonic drive will not ratchet given the radial flexibilities of the harmonic circular spline (CS), wave generator (WG), and housing, HD Systems created a finite element model of the harmonic drive and its immediate housing. HD Systems calculated that the increased length and outer diameter of the HGAG wave generators caused them to have a radial stiffness of 66×10^6 N/m, 11% higher than the standard WG stiffness. In Figure 6, HD Systems shows that since the CS housing is 55% as radially stiff as the standard CS, the minimum ratchet torque of the HGAG's harmonic drives will be 77.4 N-m.

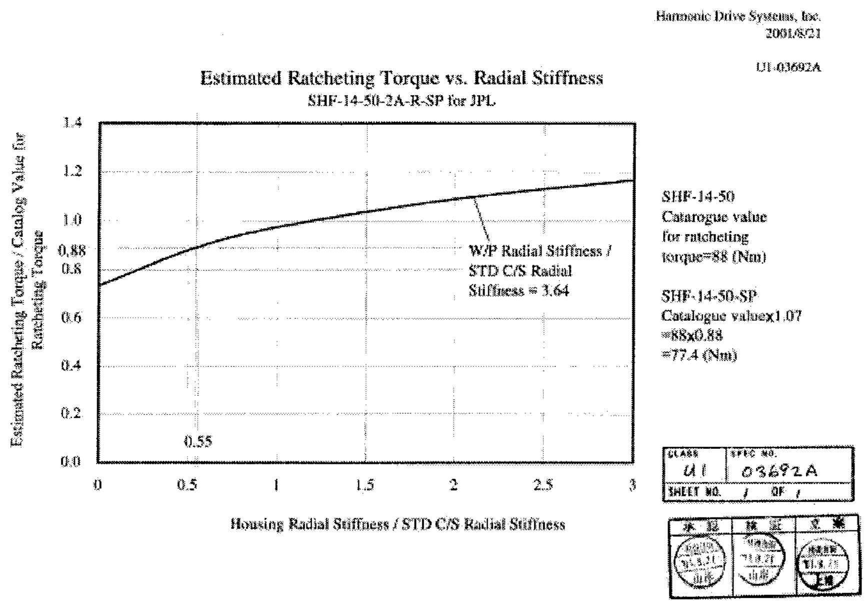

Figure 6: SHF 14-50 Ratchet Torque

<u>MER Wheel Actuators: An Overview</u>

In designing a robotic vehicle for exploring the Martian surface, it is important to realize that all parameters of the vehicle's operating environment will not be known during the design phase. In fact, the very purpose of this type of mission is to traverse unexplored terrain, unlocking the planet's geological, chemical, and even biological past. This leaves considerable amounts of missing information when it comes to developing the bounding requirements, particularly true for any system that must interact with the surface, such as the vehicle's mobility system. Because of the unknown nature of the landing site, the requirements on such a surface system can be significant. It must be capable of traversing a wide variety of terrain, from sand dunes to volcanic outflows. It must stabilize the vehicle for high pitch and tilt angles and also establish a large enough footprint to minimize ground pressure. It must be capable of climbing most obstacles in its path, while being versatile in its navigability around features it cannot safely traverse. Finally, the drive train must provide enough power to minimize the probability that the vehicle will be immobilized.

Because of this uncertainty, the MER project has developed a mobility system that is robust to variations in the environment that it will explore. Figure 7 shows the MER mobility system components.

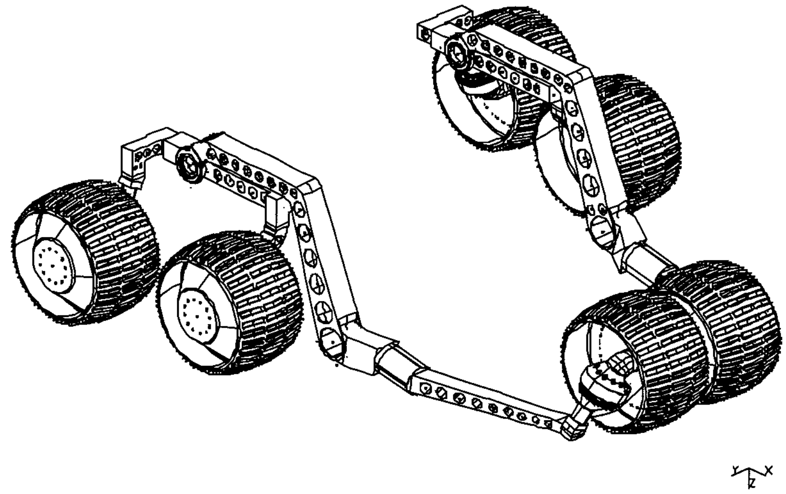

Figure 7: MER Mobility System (stowed)

The vehicle is equipped with six 25 cm diameter, 16 cm wide wheels, all of which are independently actuated. The four corner wheels also steer, giving the vehicle the ability to perform both arcing turns as well as turn-in-place maneuvers. The steer axis of these four wheels is king-pinned, or canted towards the chassis, by 20 degrees, allowing the total steering angle to be increased. Due to stringent volumetric constraints, packaging the steering actuators inside the corner wheels became necessary. This caused the drive actuator to be pushed further over to the outside of the wheel width. The configuration of the actuators within the wheel volume is shown in Figure 8.

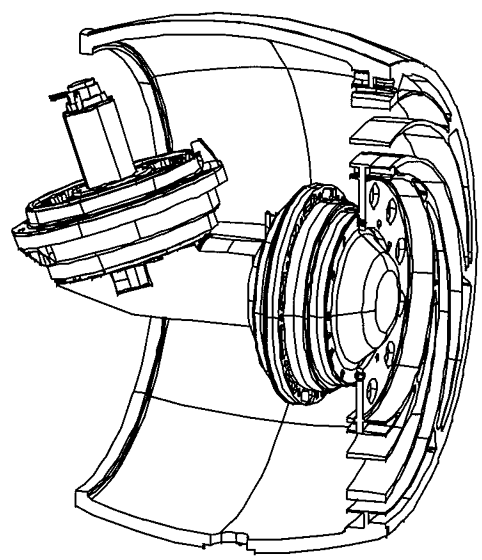

Figure 8: Configuration of Wheel Actuators

The requirements on the MER wheel actuators come from both the desire for system robustness as well as critical mission parameters. The vehicle must have a 5 cm/s surface speed requirement on a hard, flat surface. In addition, the actuator's torque requirement is directly related to the vehicle's mass of 185 kg. In order for the vehicle to avoid being torque-limited, each wheel drive actuator must be capable of applying one-half the Mars vehicle weight in thrust at the wheel rim, which results in an output torque of 43 N-m. In concert, each steering actuator must be capable of applying one-half the Mars vehicle weight in thrust at the outside wheel edge, corresponding to an output torque of 30 N-m. In addition to its torque requirement, the drive actuator must be capable of holding position with the vehicle at a 45-degree angle. The steering actuator must be capable of holding its position while the drive actuator is operating.

MER Wheel Actuators: Detailed design

Since the torque requirements of the two actuators were similar, and component commonality was necessary due to a tight development schedule, a common actuator was developed for both the drive and steering applications. Given the ground speed requirement of 5 cm/s on the drive actuators, an output rotational speed of 3.62 rpm was necessary. Given the Maxon RE25 motor's no-load speed of 6170 rpm at the nominal 28V bus voltage, a target gear reduction of 1500:1 for the wheel actuator was established.

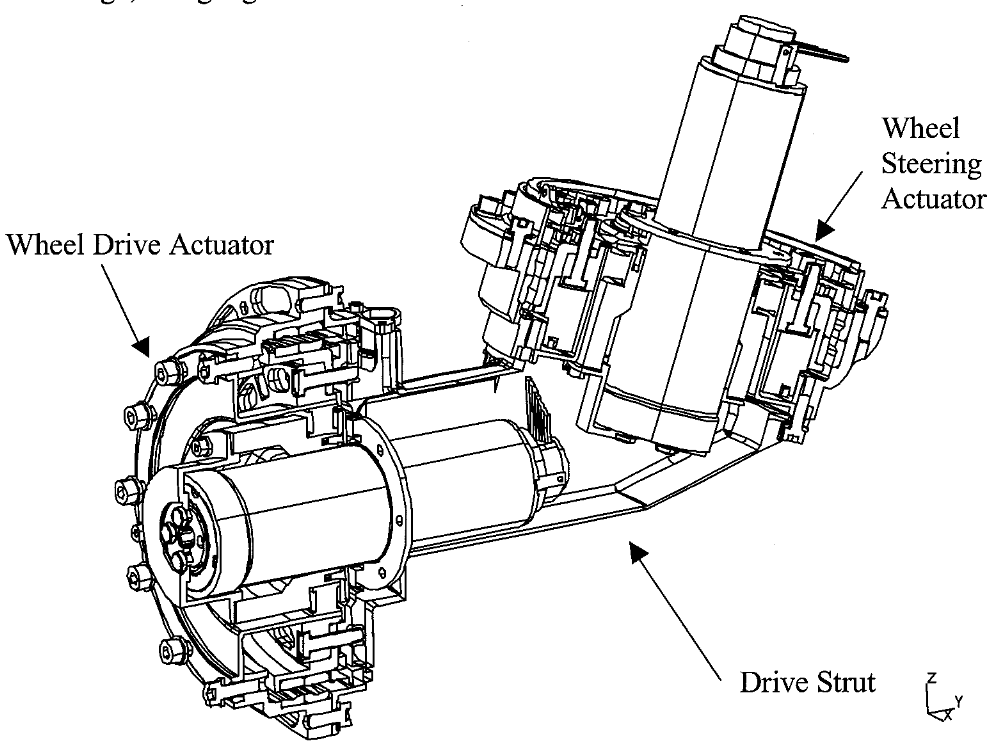

Figure 9: Cross Section of Wheel Assembly (Wheel Removed)

A detailed cross-sectional view of the wheel actuator is shown in Figure 9. A Maxon RE25 motor with a two-stage 18.8:1 planetary gearhead provides input power to the actuator. A 21mN-m magnetic detent device was added at the motor input to ensure that the actuators will hold position against external loads while the actuators are not powered. However, the planetary gearing designed for use on MER actuators was not designed for the output torques needed for either drive or steering applications. A more robust output stage was needed, so it was decided to utilize a harmonic drive for this purpose. The HD Systems hollow shaft, or "silk hat", configuration was determined to be the most appropriate for use in the wheel actuator. The SHF-20 configuration with an 80:1 gear reduction was chosen, giving the actuator a total gear reduction of 1502:1. Due to volumetric constraints, the gearmotor was packaged through the inside of the harmonic drive. This was accomplished by increasing the inner bore diameter of the wave generator plug to 29 mm, leaving a 1 mm radial clearance to the gearmotor. The gearmotor output is directly connected to the wave generator input by means of an interface cup. The circular spline was also pocketed to remove mass. Both changes reduced the radial stiffness and thus the ratchet torque capability of the harmonic drive. Figure 10 shows the effect of these modifications on ratchet torque.

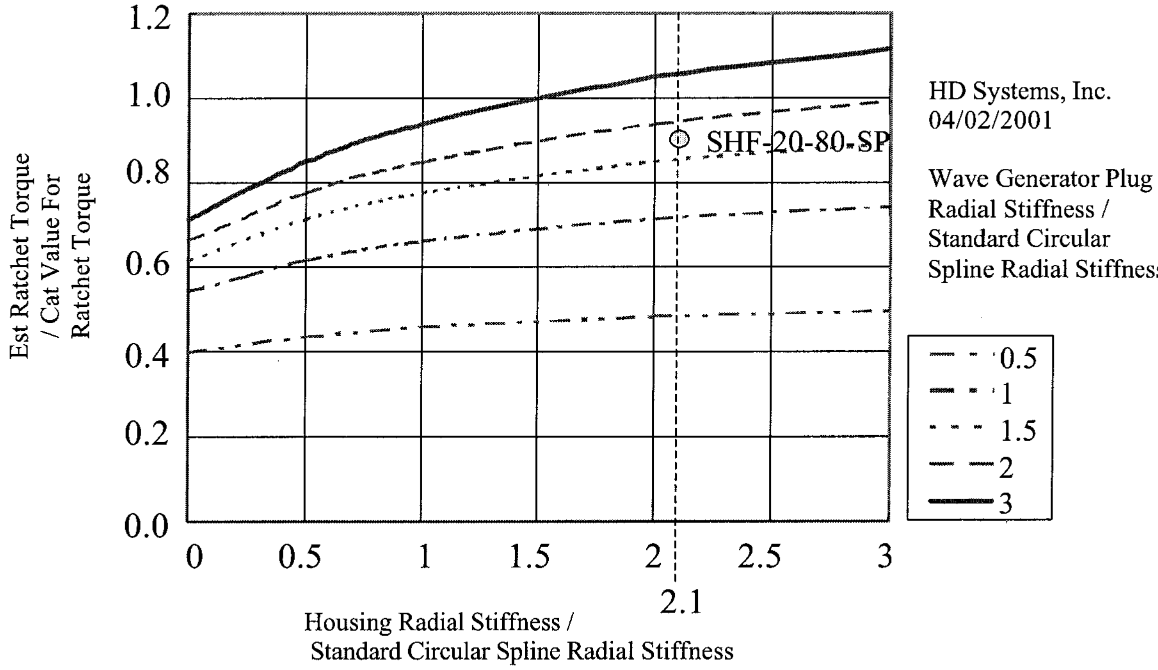

Figure 10: SHF 20-80 Ratchet Torque

As shown, the decrease in stiffness results in 90% of the catalog ratchet torque capability of the harmonic drive, or 250 N-m, an acceptable decrease in capability for this application. Due to schedule constraints, as well as a significant amount of JPL flight heritage, all harmonic drives on the rovers use commercial materials. A duplexed pair of thin-section angular contact bearings supports the output stage from external loading. A double seal design, using a spring-energized Teflon seal as a primary barrier and a Nomex felt ring as an outer barrier, has been incorporated to protect the actuators from debris contamination on the Martian surface. Both bearing and harmonic drive surfaces are grease-plated and then filled 10% by volume with Braycote 601EF grease. Since the HGAG drives use a smaller motor and are therefore more susceptible to parasitic drag internal the geartrain, the HGAG drives only use grease-plated bearings.

Development testing performed on the Harmonic Drives

Designing an actuator to operate in the wide temperature range on Mars is a difficult task. Actuators on MER are required to meet their torque, speed, and accuracy requirements at any temperature between –70C +45C and must survive between –120C to +110C. The +110C temperature results not from the space environment but from the bake-out temperature required to reduce biological burden to fulfill NASA's planetary protection requirements.

The parasitic drags and efficiencies of actuators vary widely over the actuators' operating temperature ranges. Even though Braycote 601EF is far less viscous than most other greases at low temperatures, its viscosity can nonetheless increase approximately 50 times between +25C and –70 C [3]. Relevant test data on lubricated harmonic drives at these temperatures was either scarce or not well documented. Since harmonic drives' efficiencies vary with applied torque, speed, and lubricant viscosity, development testing was performed on engineering units to mitigate risk. The tests determined:

- The no load torque of harmonic drives
- The efficiency of the entire actuators

For all the tests, the harmonic drives (wave generator bearing, flex spline, and circular spline) were grease plated with a 10% by weight solution of Castrol's Braycote 601 EF. For the efficiency testing, the angular contact ball bearings were also grease plated with a 10% solution of Castrol's Braycote 601 EF. Prior to cooling the thermal chamber for these tests, the chamber was purged with dry nitrogen gas for 10 hours.

No load torque of harmonic drives

The first series of tests found the starting and running torques of an SHF 14-100, CSF 14-50, and a CSF 20-80. No load resisted the motion of the flex spline output in these tests. The drives' respective angular contact bearings were also excluded from these tests. Flex couplings at the wave generator input minimized the drag produced by rotor eccentricities. A circular plate bolted to the flex spline and also attached to the harmonic drive input through a greaseplated bearing ensured that the flex spline was restrained axially. A picture depicting the test hardware outside and inside the thermal chamber is shown in Figure 11 and Figure 12, respectively. Figure 13, Figure 14, and Figure 15 contain the results of the no-load running torque tests for the harmonic drives, and show:

- Between room temperature and – 55 C, there exists a clear relationship between input torque, input speed, and operating temperature.
- While data obtained at –70 C does indicate a similar relationship, it is likely that frictional heating during operation at higher speeds warmed the lubricant, resulting in a lower input torque.
- Between room temperature and –55 C, the CSF-14-50 and CSF-14-100 have similar no-load running torques.
- Starting torque is consistently higher than low-speed running torque.

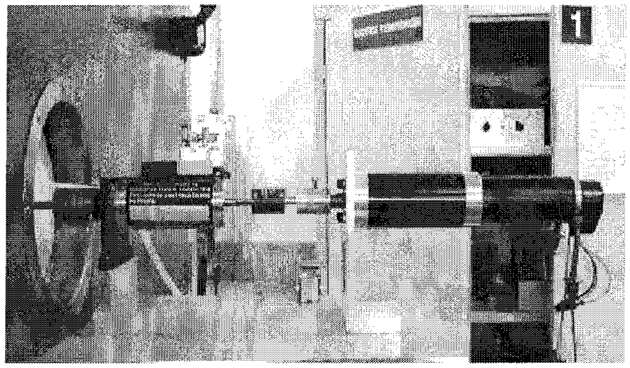

Figure 11: Motor and Torque Transducer

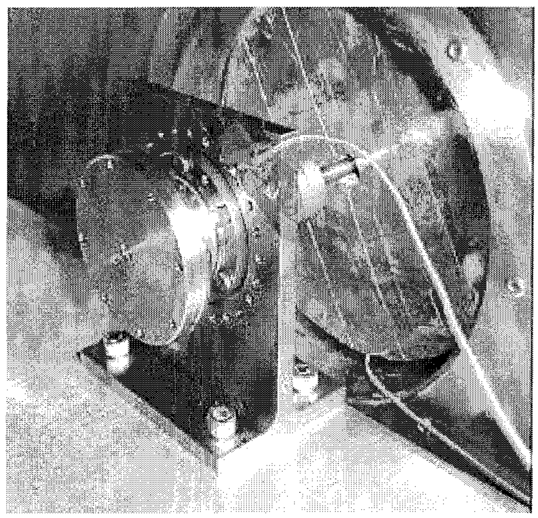

Figure 12: HD No Load Test Setup

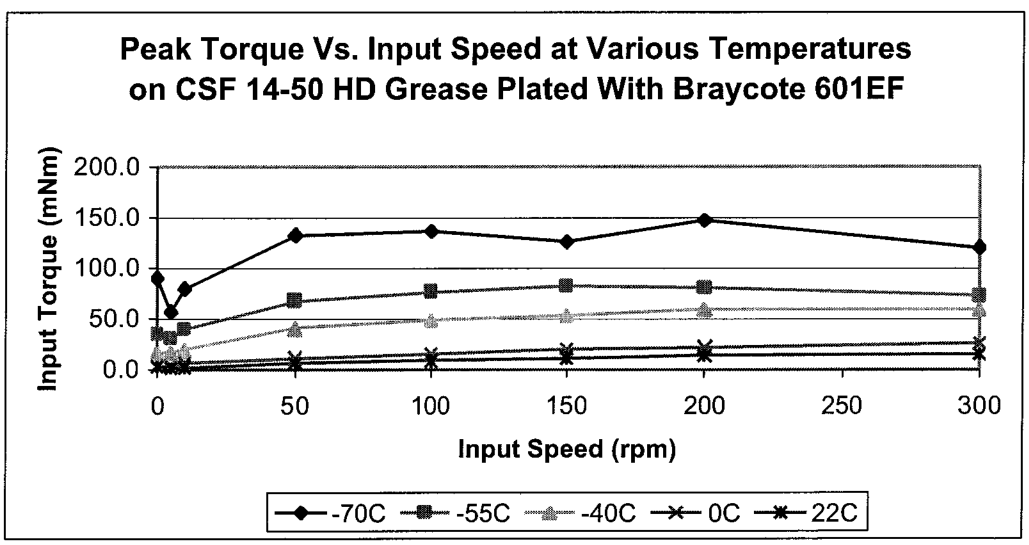

Figure 13: CSF 14-50 No Load Test Results

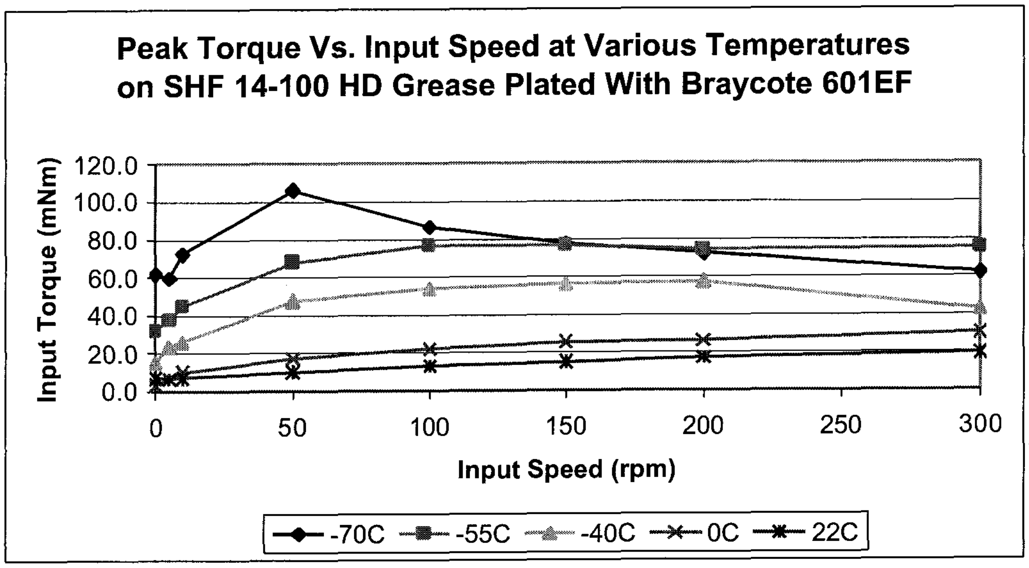

Figure 14: SHF 14-100 No Load Test Results

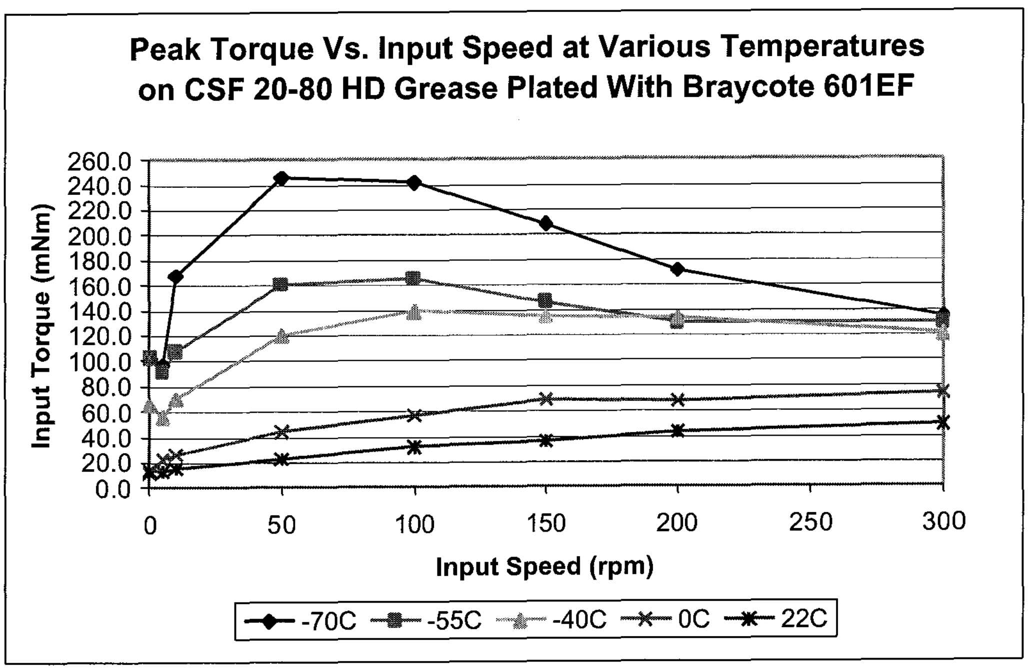

Figure 15: CSF 20-80 No Load Test Results

Efficiency of the Entire Actuators

To verify that the efficiency of the MER actuators was acceptable, the engineering units were subjected to varying speeds, torques, and temperatures. The result of this testing only characterized the output stage of both drives, however, since neither engineering unit included the actual motor and planetary gearbox.

Figure 16 depicts the setup of test hardware for the drive efficiency characterization. The test articles used in this series were high fidelity engineering units of the MER wheel actuator and HGAG output stages. Included in the models were the actuator's harmonic drive, output support bearings, support housing structures, and the appropriate type and quantity of lubrication. The HGAG engineering unit also included a set of preloaded angular contact input bearings that support the harmonic drive's wave generator. These input bearings preceded the harmonic drive in the gear train.

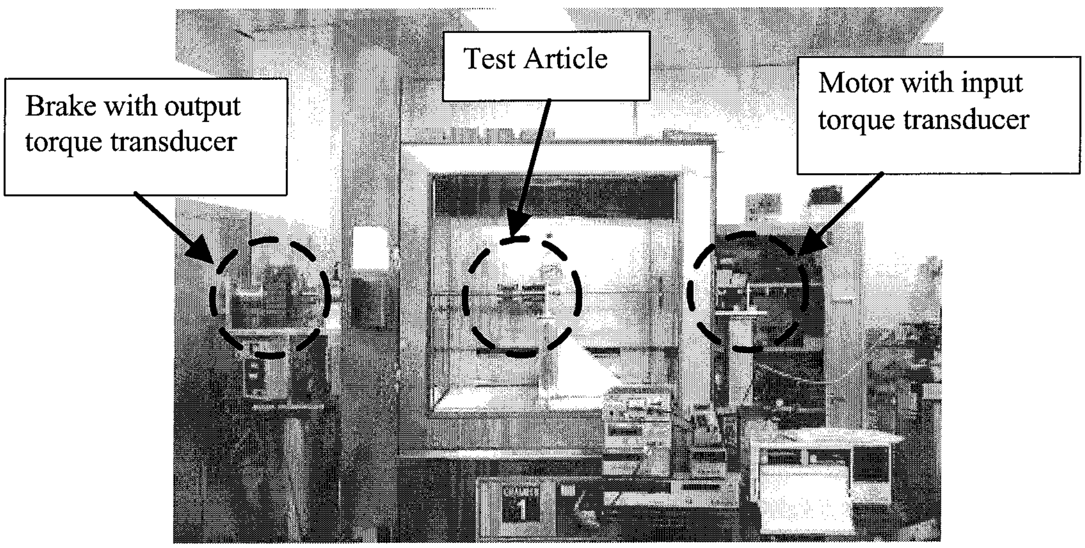

Figure 16: Wheel/HGAG Actuator Efficiency Test Setup

Figure 17 shows the engineering unit of the HGAG actuator.

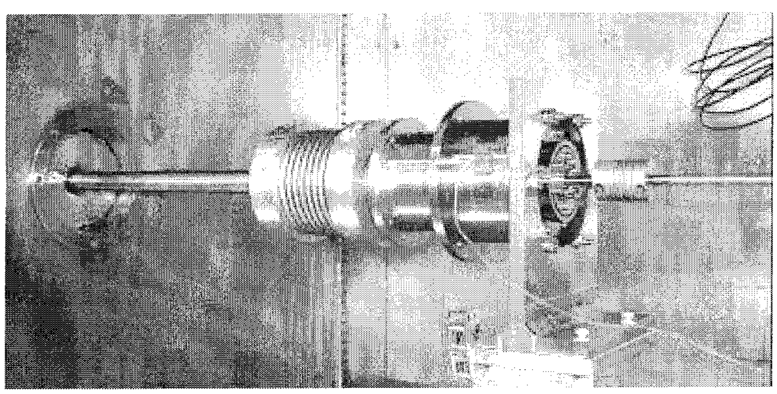

Figure 17: HGAG Engineering Unit During Efficiency Test

Efficiency Test Results

The above test program yielded more than 180 separate measurements of each test unit's input torque characteristics. This data was compiled to determine the effect of speed, applied torque, and temperature on the efficiency of each drive. While the test results for the wheel drives include the relatively small effects of drag torque from the output support bearings, the results still provide a good indication of the harmonic drive's inherent characteristics.

Figure 18 and Figure 19 depicts the variation in efficiency as a function of speed and applied external torque of the engineering units of the HGAG and wheel drives at –70 deg. C, respectively. Figure 20 and Figure 21 depicts the variation in efficiency as a function of speed and temperature at the rated torque of the HGAG and wheel drives, respectively. These results indicate the following:

- In general, the drive's efficiency reduces with decreasing temperature. However, at low temperatures, this relationship is countered by frictional warming of the lubricant.
- Once the external torque exceeds the drive's rated torque, the unit's efficiencies are relatively insensitive to increasing external torque.
- Since starting torque exceeds low-speed running torque, the drive is more efficient under stall condition than it is under a starting condition.
- The efficiency of the HGAG unit is lower that that of the Wheel Actuator unit due to the drag of the HGAG's input angular bearings.

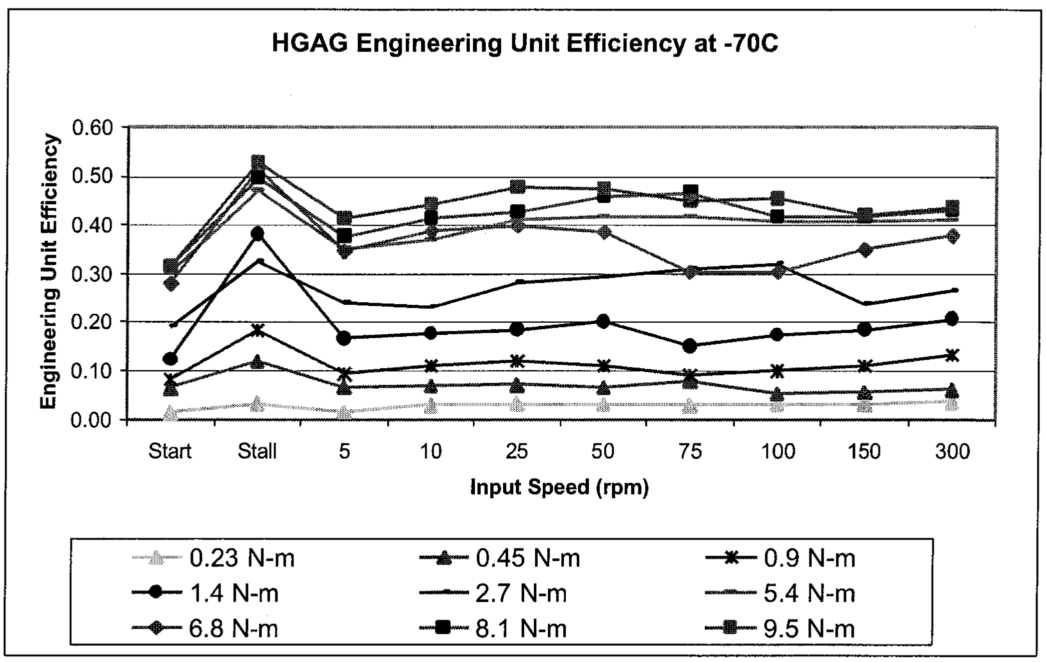

Figure 18: HGAG Engineering Unit Efficiency at -70C

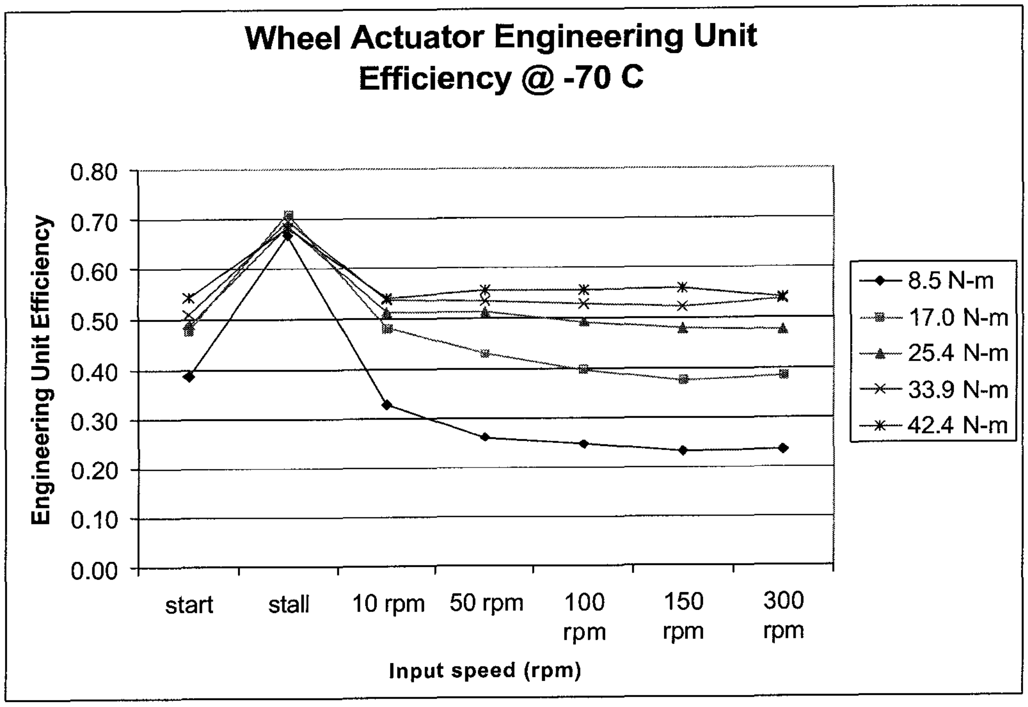

Figure 19: Wheel Drive Efficiency at -70C

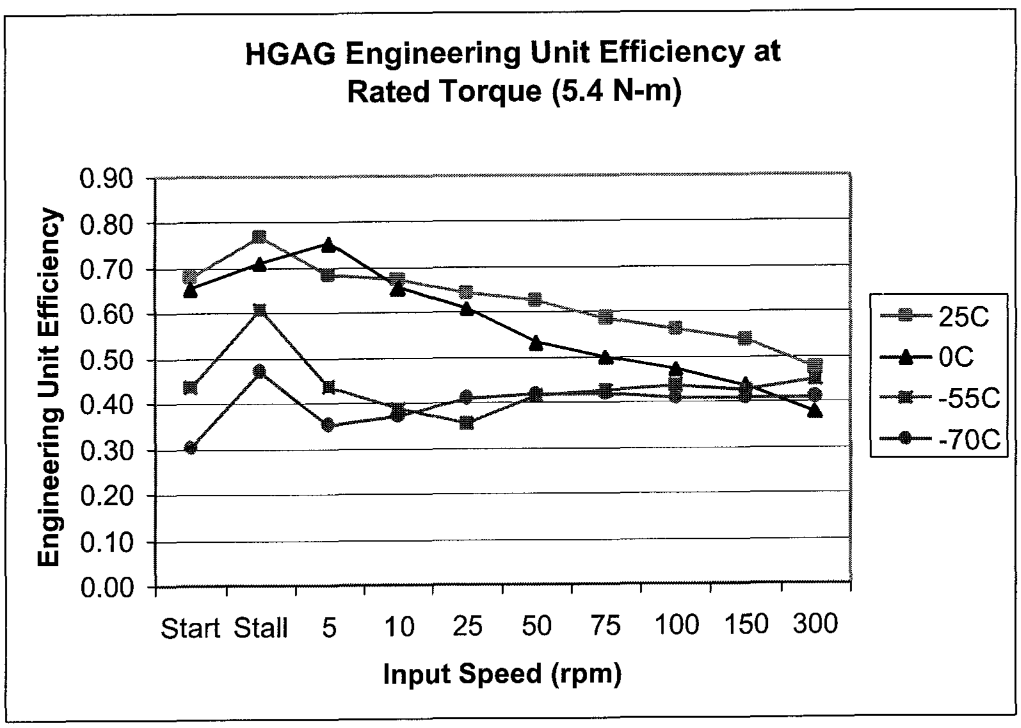

Figure 20: HGAG Engineering Unit Efficiency at Rated Torque (5.4 N-m)

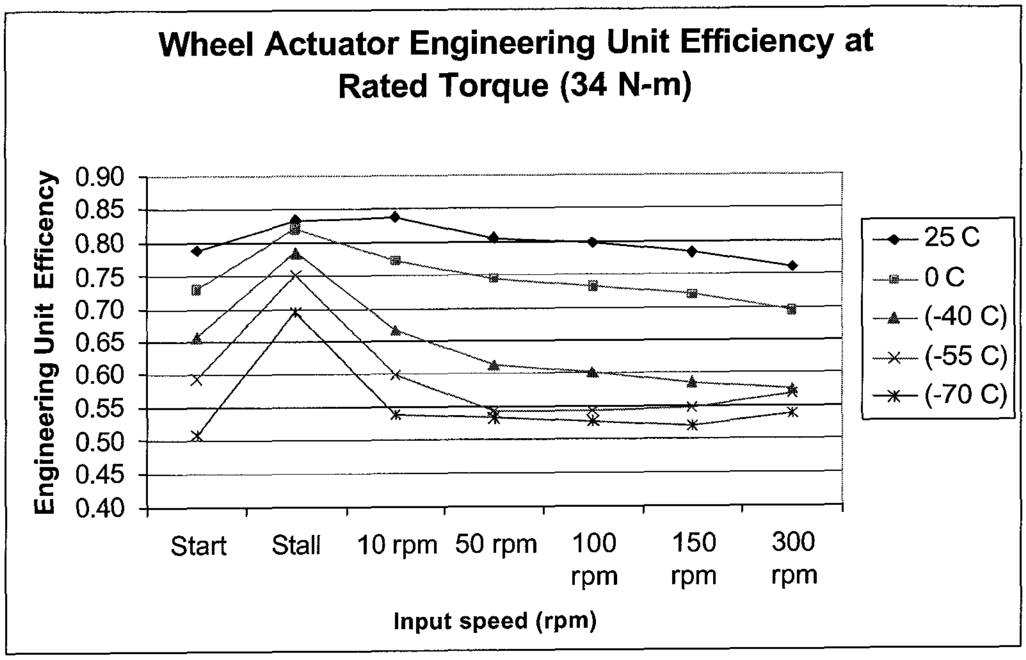

Figure 21: Wheel Drive Efficiency at Rated Torque (34 N-m)

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3. Bray 815Z oil viscosity was given in commercial product data sheet from Castrol International, plotted on ASTM Standard Viscosity – Temperature Charts for Liquid Petroleum Products (D341), 2000